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**RELATION OF LATTICE PARAMETERS
TO FRICTION CHARACTERISTICS OF
BERYLLIUM, HAFNIUM, ZIRCONIUM, AND
OTHER HEXAGONAL METALS IN VACUUM**

by Donald H. Buckley and Robert L. Johnson

Lewis Research Center

Cleveland, Ohio



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SUMMARY

The friction characteristics for three hexagonal metals (zirconium, hafnium, and beryllium) were determined in vacuum. The relation of these metals with crystal parameters and shear stress is discussed. Friction experiments were conducted with a hemispherical rider sliding on the flat surface of a rotating disk. The rider was loaded to 1000 grams, and experiments were conducted to surface speeds of 2000 feet per minute. Experiments were conducted with the metals sliding on themselves and on 440-C stainless steel.

Zirconium and hafnium showed a decrease in friction with increase in sliding velocity, while beryllium exhibited an increase in friction coefficient with increase in sliding velocity. This relation can be related to resolved shear stresses and in turn to crystal lattice parameters. The decrease in friction characteristics with sliding velocity of zirconium can be related to lattice parameters. A general relation was found between 14 hexagonal metals and their crystal lattice parameters.

INTRODUCTION

Metals with hexagonal structure (hexagonal metals) have generally better friction and wear characteristics than metals with cubic structures (cubic metals) (refs. 1 to 4). Further, the friction and wear characteristics differ considerably for those hexagonal metals that undergo crystal transformations from one crystalline form to another. The hexagonal form of these metals exhibits friction and wear characteristics that are superior to those of the cubic form of the metals where the transformation is from the hexagonal to the cubic structure (refs. 2 to 4).

If only the hexagonal metals are considered, differences are observed in friction and wear characteristics for these metals. One metal that exhibits relatively poor friction and wear properties is titanium. The friction and wear characteristics observed for titanium may be related to the mechanism of slip in the crystal of titanium (ref. 5). With those metals possessing ideal or nearly ideal close packing (e.g., cobalt, cadmium, and zinc), slip (and consequently shear) is principally on the basal plane (0001). With the metal titanium, however, the predominant slip planes are the $\{10\bar{1}0\}$ planes rather than the basal plane.

Differences in friction characteristics for various planes of single crystals of the cubic metal copper have been noted (refs. 6 and 7). The friction varied by as much as a factor of 4 with varied crystal orientations. In reference 3 for single-crystal cobalt (hexagonal) sliding on polycrystalline cobalt, a marked difference in friction was observed between the (0001) plane oriented parallel to the direction of sliding and on the $(1\bar{1}00)$ plane.

The metals zirconium and hafnium crystallographically behave very similarly to titanium in their slip mode ($\{10\bar{1}0\}$ slip). The friction characteristics for these two metals were therefore determined. The metal beryllium also has a hexagonal crystal structure, with lattice ratio c/a similar to that of titanium, zirconium, and hafnium. Unlike these metals, however, the predominant mode of slip is on the basal plane (refs. 8 to 10). Because of its light weight, beryllium is desirable for space applications. Good friction and wear characteristics would make beryllium very attractive for lubrication systems intended for space.

The objectives of this investigation were to determine in vacuum (1) the friction characteristics of zirconium, hafnium, and beryllium, (2) the relation between friction and lattice ratio c/a of these metals, (3) the difference in friction and wear between these metals and the cubic transition metals (copper and nickel), and (4) the effect of interbasal planar spacing on the friction characteristics of hexagonal metals. Experiments were conducted with a hemispherical rider sliding on a flat disk (the metal under examination on itself and on 440-C stainless steel) under a load of 1000 grams at sliding velocities to 2000 feet per minute.

APPARATUS

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens (a $2\frac{1}{2}$ -in.-diam. flat disk and a $\frac{3}{16}$ -in.-rad. rider) mounted in a vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The driver magnet, outside the vacuum system, was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing (cutaway in fig. 1) and was mounted on one end of the shaft within the cham-

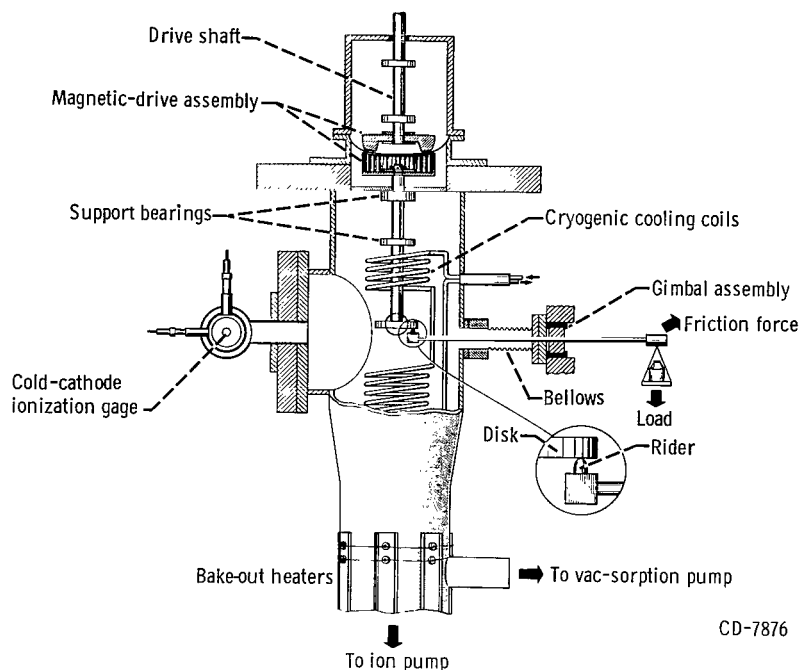


Figure 1. - High-vacuum friction and wear apparatus.

tion pump and a vac-sorption forepump. The pressure in the chamber was measured adjacent to the specimen with a cold-cathode ionization gage. In the same plane as the specimens and the ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system. A 20-foot 5/16-inch-diameter stainless-steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

SPECIMEN FINISH AND CLEANING PROCEDURE

The disk and rider specimens used in friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and the rider were given the same preparatory treatment: (1) a thorough rinsing with acetone to remove oil and grease, (2) a polishing with moist levigated alumina on a soft polishing cloth, and (3) a thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

RESULTS AND DISCUSSION

Zirconium

The friction data obtained in reference 5 for 99.99 percent titanium sliding on tita-

ber. The end of the shaft opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm away from the rider specimen was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a deadweight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ioniza-

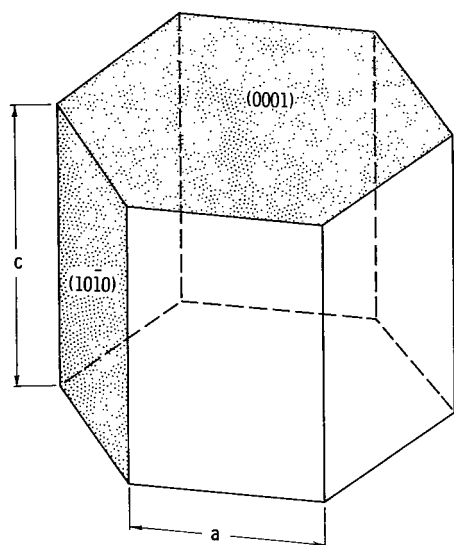


Figure 2. - Hexagonal crystal.

nium and on 440-C stainless steel indicate that slip on the $(10\bar{1}0)$ plane results in higher friction than that found for the hexagonal transition metal cobalt when basal slip (0001) occurs (ref. 3). These two crystal planes are shown in figure 2. Two metals among the transition series that have properties very similar to those of titanium are zirconium and hafnium. Because of the extreme similarity in these two elements, the slip mechanisms can be expected to be the same. References 11 and 12 indicate that this is in fact the case. The friction behavior of zirconium and hafnium might therefore be expected to be very similar to that of titanium. Table I indicates the slip systems for these metals.

The friction coefficients for 99.99 percent zirconium sliding on zirconium was measured in vacuum at various sliding velocities, and the results obtained are presented in figure 3(a). The friction coefficient was in excess of 1.0 at 25 and at 500 feet per minute. At approximately 700 feet per minute, the friction coefficient was less than 0.4 and decreased to 0.2 at 2000 feet per minute. When the velocity was reduced after running at 2000 feet per minute, the friction coefficient at sliding velocities less than 500 feet per minute remained relatively low. The relatively low values obtained at these velocities may be associated with the fact that the specimens were still considerably above the temperatures

TABLE I. - CRYSTALLINE PROPERTIES OF VARIOUS HEXAGONAL METALS

Metal	Atomic radius, Å	Interatomic distance		Lattice ratio, c/a	Slip plane	Slip direction	Critical resolved shear stress, kg/sq mm
		a, Å	c, Å				
Cobalt	1.162	2.502	4.061	1.624	(0001)	$[2\bar{1}\bar{1}0]$	0.675
Hafnium	1.442	3.200	5.077	1.587	$\{10\bar{1}0\}$	----	-----
Beryllium	.889	2.281	3.577	1.568	$\{^a(0001)\}$	$[11\bar{2}0]$	1.40
					$\{10\bar{1}0\}$	$[11\bar{2}0]$	6.69
Zirconium	1.454	3.223	5.123	1.592	$\{10\bar{1}0\}$	$[11\bar{2}0]$	----
					(0002)	$[11\bar{2}0]$	----
Titanium	1.324	2.953	4.729	1.587	$\{10\bar{1}0\}$	$[11\bar{2}0]$	5.0
					(0002)	$[11\bar{2}0]$	11.0

^aPredominant slip plane at room temperature.

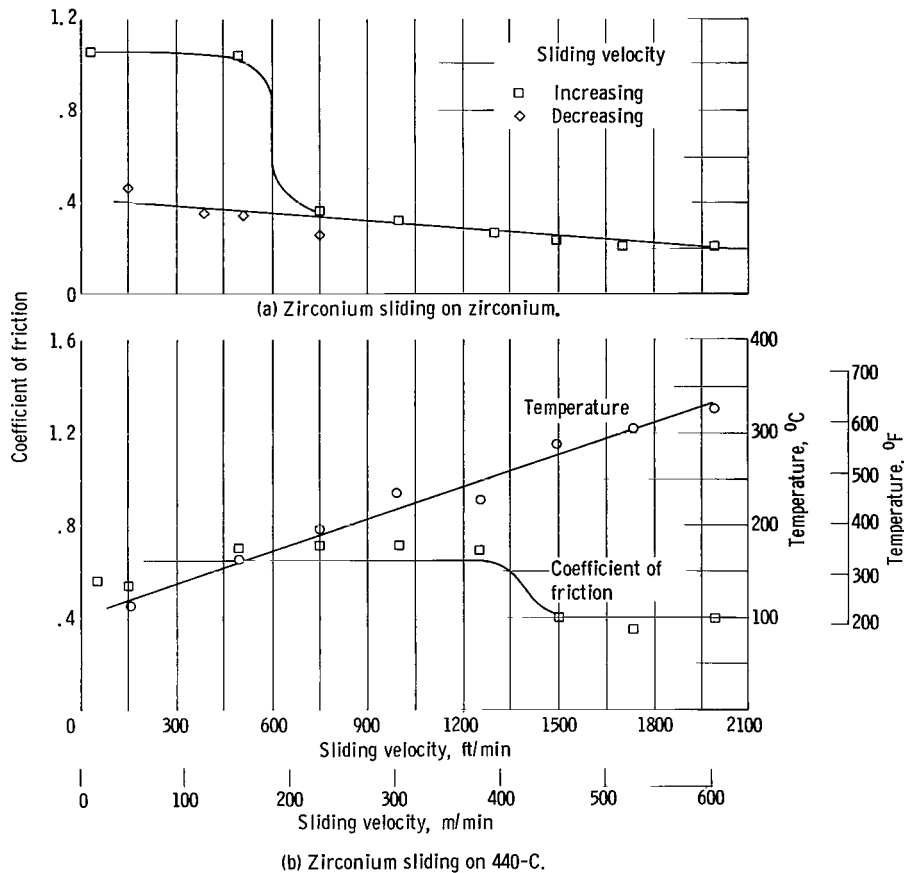


Figure 3. - Coefficient of friction for 99.99 percent zirconium sliding on 99.99 percent zirconium and on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load; 1000 grams; no external heating.

that would be obtained with the specimens in the initial portion of the experiment.

The friction characteristics for 99.99 percent zirconium sliding on 440-C stainless steel were determined at various sliding velocities in vacuum, and the results obtained are presented in figure 3(b). The friction decreased at a sliding velocity of approximately 1400 feet per minute.

An examination of the lattice ratios c/a for hexagonal zirconium shown in figure 4 indicates that this ratio increases with increasing temperature. Based on similar results obtained with titanium in reference 5, a gradual decrease in friction with increasing sliding velocity (interface temperature) might be anticipated. Although a decrease in friction was observed for zirconium sliding on zirconium (fig. 3(a)), the decrease at a velocity of about 600 feet per minute was very abrupt.

The c/a lattice ratio does not indicate any such abrupt changes. If, however, the c/a lattice ratio is separated into its individual components, the reason for abrupt change in friction may be better explained. The lattice parameters c and a of hexag-

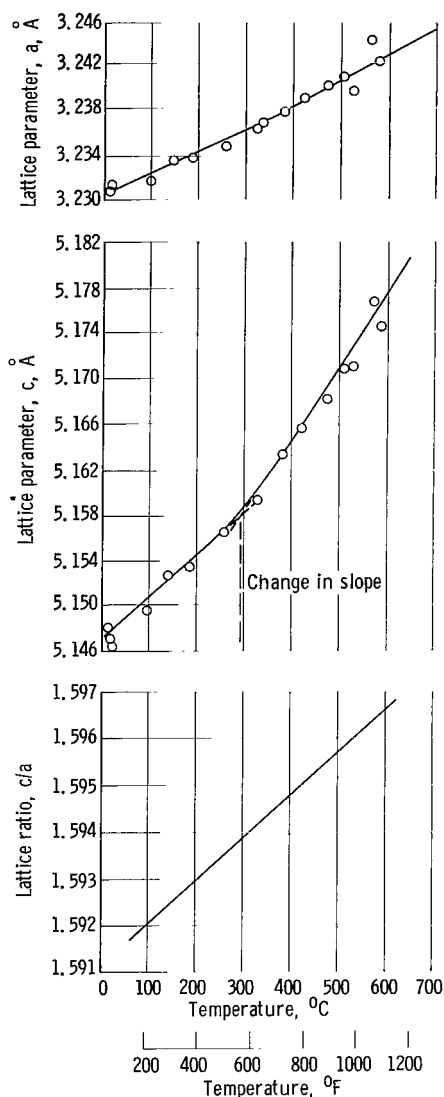


Figure 4. - Lattice parameters for zirconium as function of temperature (from ref. 12).

onal zirconium measured at various temperatures are presented in figure 4 as obtained from reference 12.

Examination of figure 4 indicates a marked change in the slope for the lattice parameter c at a temperature of approximately 600°F (315°C). This marked change in lattice spacing may account for the change in friction characteristics observed at a sliding velocity of about 700 feet per minute. In the experiment with the 440-C disk, the rider-specimen (zirconium) temperatures were measured (fig. 3). Temperatures of 500° to 600°F were measured at those sliding velocities associated with the friction change.

Although the predominant mode of slip at room temperature for zirconium is on the $\{10\bar{1}0\}$ planes, it is not the only mode, as indicated in table I. Slip on the basal plane also occurs, but to a lesser degree. If, however, the axis continues to expand as shown in figure 4 with increasing temperature, then the tendency to slip on the basal plane will continue to increase with increasing temperature (ref. 12). At high temperature, it may be the preferred mode of slip. With a continued increase in interplanar spacing (c lattice), a decrease in shear stress for basal shear might be anticipated.

Hafnium

The friction characteristics were measured for 99.99 percent hafnium sliding on 99.99 percent hafnium and on 440-C stainless steel. The results obtained in these studies are presented in figure 5. The friction coefficient for hafnium sliding on hafnium in vacuum was relatively high but decreased with increasing sliding velocity (fig. 5(a)). This result was also noted with hafnium sliding on 440-C stainless steel. On 440-C at sliding velocities in excess of 1000 feet per minute the friction was less than 0.3. Data (other than at room temperature) could not be found on the measured lattice parameters c and a for high-purity hafnium. Based on friction data obtained in this investigation with hafnium and zirconium (and titanium obtained in ref. 5), hafnium would be expected to show an increase in the c/a lattice ratio with temperature.

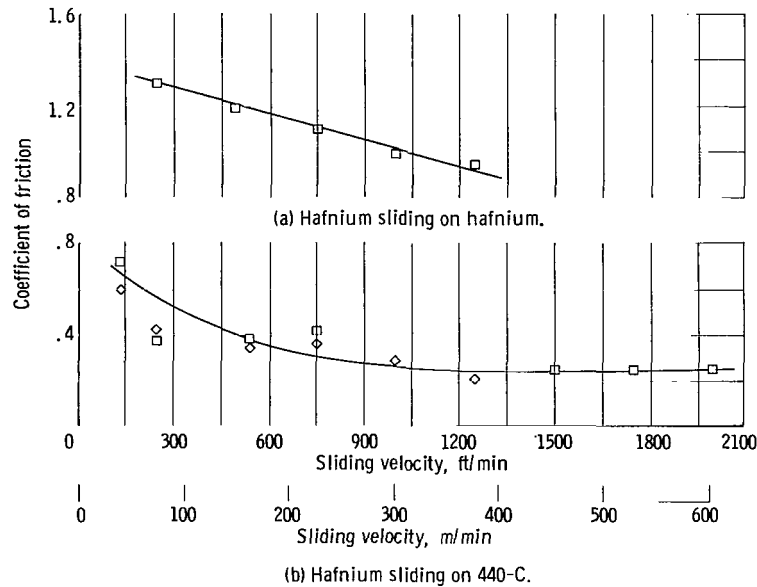


Figure 5. - Coefficient of friction for 99.99 percent hafnium sliding on 99.99 percent hafnium and on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external heating.

Beryllium

Although beryllium has a c/a lattice ratio very near that of titanium, zirconium, and hafnium, its primary mode of slip is on the basal plane (0001). Based solely on the c/a lattice ratio, beryllium might be expected to have a slip system similar to that of hafnium. If, however, size factor and interatomic bonding forces are considered, the reason for slip on the basal plane in beryllium can be more easily seen. A consideration of bond forces may be made using the following simple equation from reference 13:

$$k^{-1/2} = a(D - b)$$

where k is the bond force in megadyne per centimeter, a and b are constants for a particular metal, and D is the internuclear distance in angstroms.

For interatomic bonding in the c -axis, a force of 20.6×10^{-3} megadyne per centimeter was calculated for beryllium, a force of 33.7×10^{-3} megadyne per centimeter for zirconium, and 31.4×10^{-3} megadyne per centimeter for titanium. Because of interatomic interaction within a plane, these values can be considered only approximations, but they do give an indication of differences in bond forces. Based on the slip mechanism of beryllium, friction coefficients comparable with that obtained with cobalt in reference 3 might be anticipated.

Friction experiments were conducted in vacuum with beryllium metal sliding on beryllium metal at various sliding velocities, and the results obtained are presented in

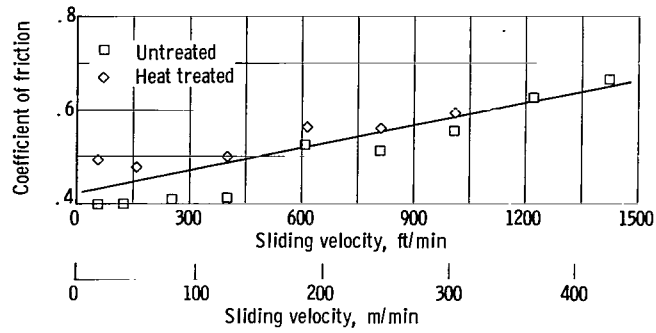


Figure 6. - Coefficient of friction for beryllium sliding on beryllium in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external specimen heating.

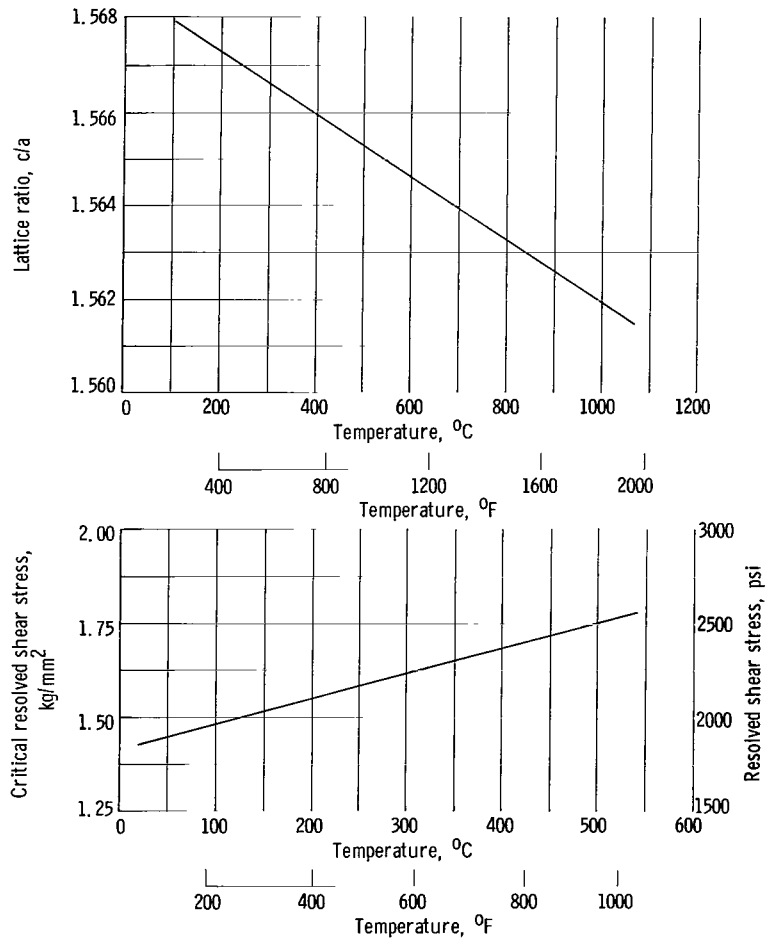


Figure 7. - Effect of temperature on c/a lattice ratio and critical resolved shear stress for beryllium metal (from ref. 8).

figure 6. At relatively low sliding velocities the friction coefficient was similar to that obtained for cobalt in reference 3. As the sliding velocity increased, however, the friction coefficient began to increase. This increase in friction is the opposite of the trend observed for titanium, zirconium, and hafnium.

Examination of the c/a lattice ratio for beryllium as a function of ambient temperature shows the reverse trend of that observed for titanium, zirconium, and hafnium; that is, the c/a lattice ratio decreases with increasing temperature (fig. 7). Just as the c/a lattice ratio decreases, the critical resolved shear stress for beryllium increases (fig. 7), and as a consequence, an increase in friction with increasing sliding velocity (interface temperature) is observed. The critical resolved shear stress of figure 7 is for single-crystal beryllium. These values were selected because they avoid the variation in shear stress associated with grain boundaries and differences in grain size. An approximate shear stress may be obtained for polycrystalline beryllium by multiplying the values in figure 7 by 2 (ref. 8).

Cubic and Hexagonal Metals

Since the slip system for titanium, zirconium, and hafnium is not the ideal basal slip characterizing other hexagonal metals, and the friction and wear are not so low as might be encountered with ideal hexagonal metals, the friction and wear characteristics were compared for two cubic and three hexagonal metals. The object of the comparison was to determine whether the hexagonal metals that did not exhibit basal slip were superior to cubic metals in friction and wear characteristics in vacuum. The results obtained in friction and wear experiments with the cubic metals, copper and nickel, and the hexagonal metals, zirconium, titanium, and beryllium, are presented in figure 8. With the two cubic metals, copper and nickel, a load of 500 grams instead of the normal 1000 grams had to be used because complete welding of the specimens occurred with a 1000-gram load. The friction coefficients for these two metals as indicated in the figure were more than twice the values obtained for zirconium and titanium ($\{10\bar{1}0\}$ slip) and five to six times the value for beryllium ((0001) slip). Further, even with the 500-gram load, intermittent welding of the cubic metals occurred. The hexagonal metals were run under a load of 1000 grams.

Although wear is difficult to measure in vacuum because of a continuous transfer back and forth of wear material, rider specimen wear was measured upon the completion of each experiment. The resulting wear in terms of a parameter is presented in figure 8. The wear of the cubic metals is much greater than that of the hexagonal metals.

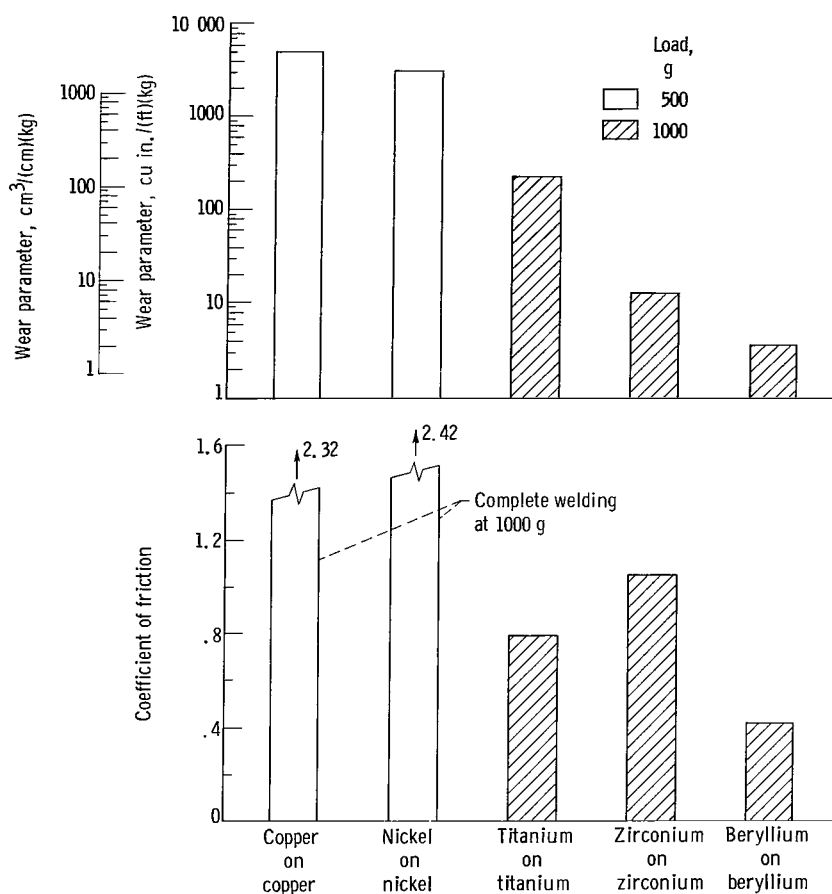


Figure 8. - Coefficient of friction and rider wear rate for various metals in vacuum (10^{-9} mm Hg). Sliding velocity, 4.5 feet per minute; no external heating of specimens; duration of test, 1 hour.

Friction as Function of Interbasal Planar Spacing for Some Hexagonal Metals

The c-axis dimension for hexagonal metals normally refers to the distance in angstroms of the unit cell, that is, the distance between outermost basal planes. Many metals have, however, more than two basal planes within the cell. Lanthanum, neodymium, and praseodymium, for example, each have three basal planes and consequently two units within the cell. Samarium, of the same series, has four basal planes. In friction studies it is not the cell dimension but the distance between adjacent basal planes that is important, since slip is initiated between these planes. In this discussion of hexagonal metals, it is therefore not the c/a lattice ratio that will be considered but rather the ratio of spacing between adjacent basal planes of the unit cell to the lattice parameter (fig. 2, p. 4).

The effect of interplanar spacing of basal planes of hexagonal metals on their friction characteristics is shown in figure 9(a), in which the coefficients of friction for various

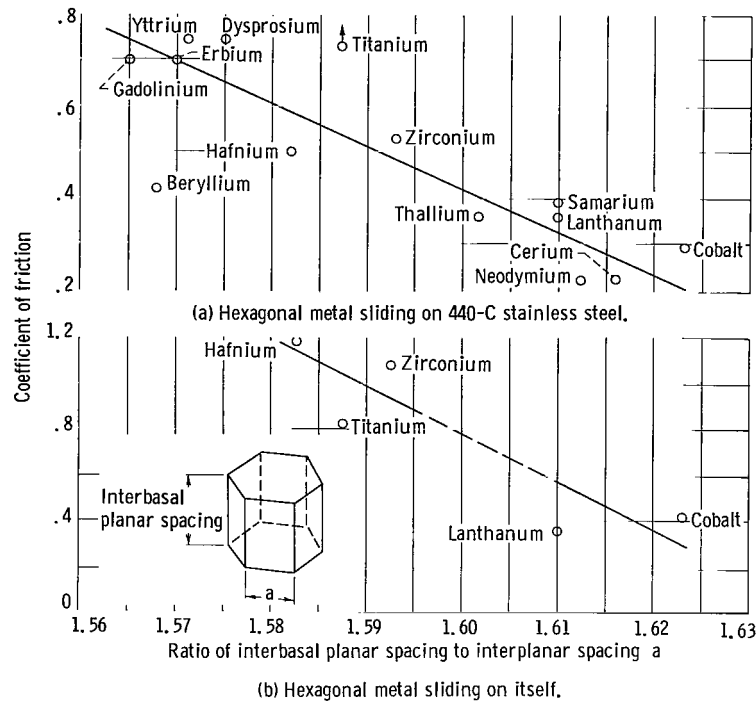


Figure 9. - Coefficient of friction for various metals as function of lattice ratio.
 Vacuum, 10^{-9} millimeter of mercury; load, 1000 grams; sliding velocity,
 400 feet per minute; no external specimen heating.

hexagonal metals are presented as a function of interbasal planar spacing. The results of figure 9(a), which summarizes the data of references 2 to 5 and of this investigation indicate a direct correlation between interbasal planar spacing and friction for hexagonal metals. The two noted exceptions are titanium and beryllium. The metal beryllium does not fall on the curve because of its basal slip mechanism, despite the lattice parameters. The atomic size of beryllium and the resulting interbasal bonding forces are less than for the metals zirconium, hafnium, and titanium with similar c/a lattice ratios. Titanium could have approached the curve had friction values been obtained at a higher sliding velocity. The particular sliding velocity for the data shown in figure 9(a) was 400 feet per minute. This sliding velocity was selected because a number of the metals included undergo crystal transformations at slightly higher sliding velocities. The results of figure 9(a) indicate direct correlation of friction properties and interbasal planar spacing for hexagonal metals. A decrease in friction was observed with an increase in interbasal planar spacing over the lattice parameter a .

In order to determine whether the relation of lattice parameters to friction characteristics could be related to hexagonal metals sliding on themselves, coefficient of friction was plotted in figure 9(b) as a function of lattice parameter as in figure 9(a). Although a limited number of points were available, the relation appears to hold for metals

sliding on themselves. A closer correlation of friction with lattice parameter for titanium exists with the metal sliding on itself than was observed with it sliding on 440-C.

SUMMARY OF RESULTS

From the friction and wear data obtained in an investigation of the relation of lattice parameters to friction characteristics of zirconium, hafnium, and beryllium in vacuum, the following results were obtained:

1. A correlation between friction characteristics and lattice ratio for close-packed hexagonal metals existed; lower coefficients of friction were obtained for those metals with the greatest interatomic distance in the interbasal planar spacing. Two exceptions to this relation were titanium and beryllium. A higher sliding velocity (interface temperature) would have correlated titanium with the other data. The atomic size factor of beryllium and, consequently, bond strength in the c-axis are believed to be responsible for its reduced friction characteristics. Although beryllium has a c/a lattice ratio near that of titanium, zirconium, and hafnium, basal slip predominates for beryllium while slip occurs in the $\{10\bar{1}0\}$ planes for zirconium, titanium, and hafnium.
2. The friction and wear for the hexagonal transition metals, zirconium, hafnium, and beryllium, were less than for the cubic transition metals, copper and nickel.
3. The friction characteristics for beryllium can be related directly to its c/a lattice ratio, bond strength (in the c-axis), and critical resolved shear stress (slip on basal planes).
4. The friction characteristics for zirconium can be related directly to slip systems, $\{10\bar{1}0\}$ slip planes, and c/a lattice ratio.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 16, 1964.

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